Constraining primordial black holes from observation of stars in dwarf galaxies

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ULB

Esser, PT, PRD 107 (2023) 10, 103052, arXiv:2207.07412

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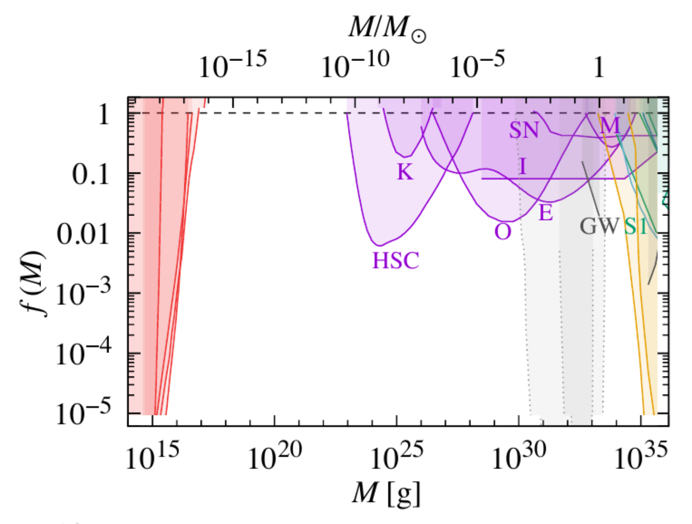
Experimental constraints

Many constraints from various arguments:

Carr, Rept.Prog.Phys. 84 (2021) 11



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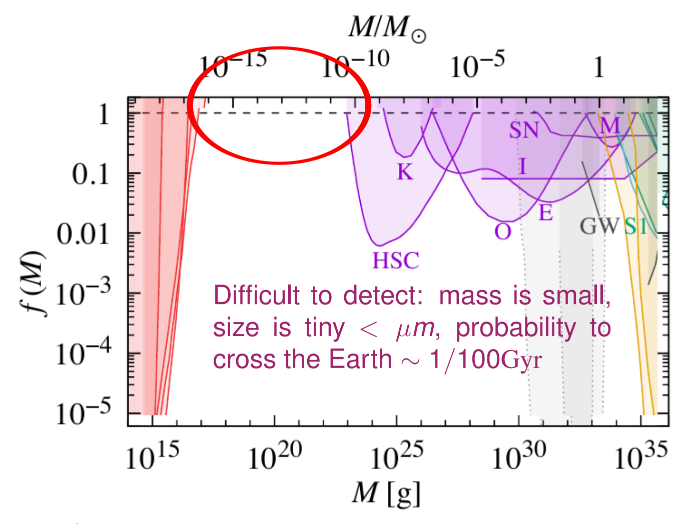


Constraints from capture of PBH by stars

- In this mass range PBH abundance may be constrained from their capture by stars
- If a PBH is captured by a star it accretes the matter and eventually destroys the star
  $\Longrightarrow$ A mere existence of stars may be used to constrain the PBH abundance.
- Previous studies concentrated on NS and WD because they capture PBH more easily.

  Capela, Pshirkov, PT, PRD87 (2013) 023507
  Capela, Pshirkov, PT, PRD87 (2013) 123524
  Capela, Pshirkov, PT, PRD90 (2014) 083507

  However, NS and WD themselves are much harder to observe.
- Here we focus on main sequence stars

Destruction of ordinary stars by PBH

How fast an ordinary star gets destroyed by a PBH?

- Assume Bondi accretion (spherically symmetric inflow of gas). The Bondi rate is

$$\dot{m}_{\rm BH} = \frac{4\pi\rho_* G^2 m_{\rm BH}^2}{c_s^3}$$

- Accretion time

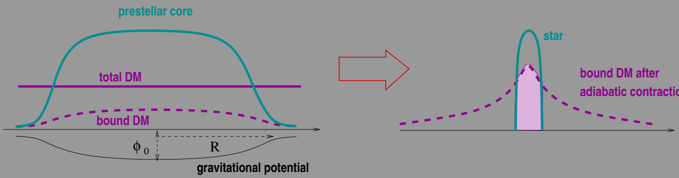
$$t_{\rm acc} = \frac{c_s^3}{4\pi\rho_* G^2 m_{\rm BH}} = 5\times 10^6 {\rm yr}\left(\frac{10^{20}{\rm g}}{m_{\rm BH}}\right) \Longrightarrow {\rm OK}$$

- Note:
  - initial stages are the longest
  - Bondi radius $r_B = 2Gm/c_s^2 \sim 5\times 10^{-3}$ cm $\Longrightarrow$ gas approximation OK

Capture at star formation

Capela, Pshirkov, PT, PRD87.023507, PRD90.083507

- The stars are formed in the collapse of giant molecular clouds. These clouds have some DM (PBH) density gravitationally bound to them with $\rho_{\rm bound} \propto \rho_{\rm DM}/\sigma^3$.
- Collapsing baryons gravitationally drag the DM along by adiabatic contraction



- At the end some PBH end up inside the star, and even more on star-crossing orbits
- The latter gradually loose energy and finally get captured as well.

Simulation of capture

Esser, PT, PRD 107(2023)10, 103052 [arXiv:2207.07412]

Two stages:

A initial capture by adiabatic contraction
- same as in previous studies, except we account for the final star density profile

B sinking into newly formed star
- time constraint
- constraint from perturbers

A. Adiabatic contraction

- Baryons are contracted from a uniform sphere of $R_c = 4300$AU to the actual star density profile
- PBH trajectories are simulated one by one in the baryon gravitational field. Those with apastron $< R_*$ are retained.
- The initial conditions of PBH uniformly sample the DM distribution. The sampled region

$$r < 20R_C, \quad v < v_{\rm esc} = \sqrt{3GM_\odot/R_C} = 0.79 \rm km/s$$

- The ambient DM distribution is assumed to be uniform in space with $\rho = 100$GeV/cm^3 and Maxwellian in velocity with dispersion $\sigma = 7$km/s (reference parameters).

B. Sinking conditions

Each successful trajectory was checked for two extra conditions:

- *Cooling time.* Rough analytic estimate:

$$t_{\rm cool} = \frac{\pi M_* R_*}{m_{\rm BH} \ln \Lambda} \sqrt{\frac{r_{\rm max}}{R_G}} \sim 10^{10} {\rm yr} \sqrt{\frac{r_{\rm max}}{100 {\rm AU}}} \frac{10^{20} {\rm g}}{m_{\rm BH}}$$

  Calculated numerically for each trajectory. Those with $t_{\rm cool} > 10^{10} {\rm yr}$ were discarded.

- *Perturbations* by nearby stars are not too big,

$$r_{\rm min} = r_{\rm max} \left(\frac{r_{\rm max}}{d} \right)^6 < R_*,$$

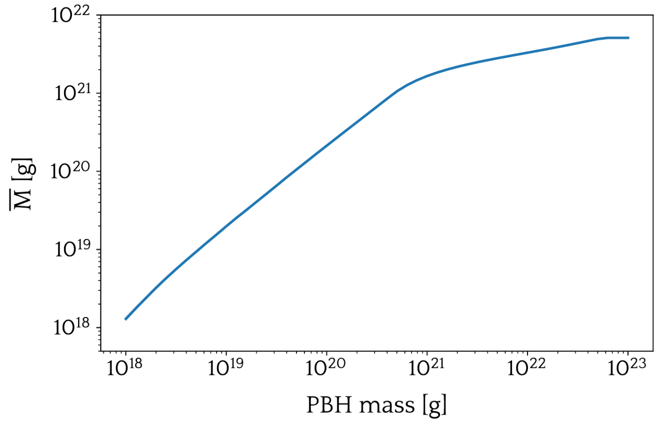
  otherwise the trajectory was discarded.

Mean captured mass

From the simulations we have

- total DM mass in the sampled region of phase space (assume for now that PBH constitute 100%)
- fraction of successful (captured) trajectories

$\Longrightarrow$ determine the mean captured mass $\bar{M}$



Mean captured mass

The probability to capture 0,1,2,.. PBH has the Poisson distribution with the mean $f\bar{M}$, f being the PBH abundance. In an ensemble of stars, the fraction ξ of destroyed stars is therefore

$$\xi = 1 - \exp(-f\bar{M}/m_{\rm BH})$$

Requiring that no more than fraction ξ of stars is destroyed gives the constraint on the PBH fraction f in DM

$$f < \frac{m_{\rm BH}}{\bar{M}} \ln \frac{1}{1-\xi}$$

The max allowed fraction ξ has to come from observations. The smaller ξ, the stronger constraints.

Some observed dwarf galaxies

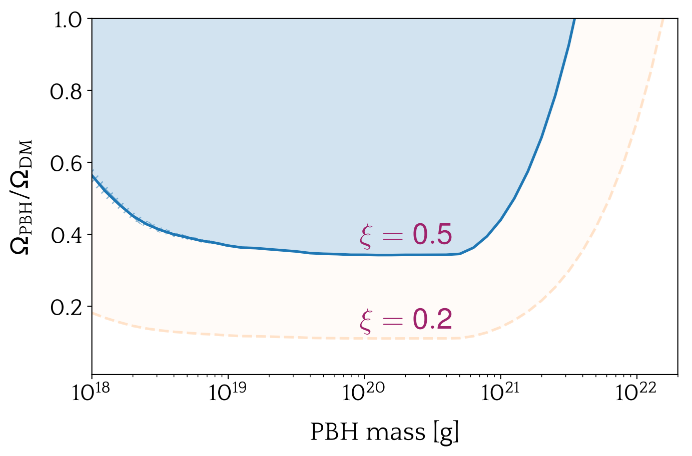
	$R_{1/2}$ [pc]	σ [km/s]	$\rho_{\rm DM}$ [GeV/cm^3]	n_* [10^{-3}pc^{-3}]	η
Triangulum II	16	< 5.9	161	9.2	0.95
Tucana III	37	< 2.1	3.7	0.67	0.51
Draco II	19	< 10.2	343	2.6	0.39
Segue 1	24	6.4	85	2.1	0.39
Grus I	28	5.0	38	9.6	0.37

Here the merit factor

$$\eta = \frac{\rho_{\rm DM}}{100{\rm GeV/cm}^3}\left(\frac{7{\rm km/s}}{\sqrt{2}\sigma}\right)^3$$

shows how the concrete galaxy is doing with respect to our reference values $\rho = 100{\rm GeV/cm}^3$ and $\sigma = 7{\rm km/s}$.

Constraints from Triangulum II



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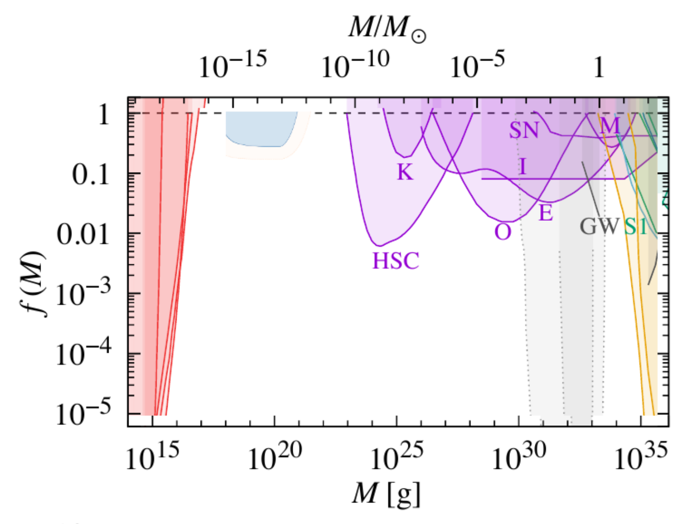


Summary

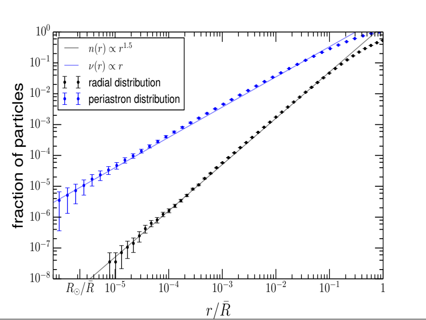
- Constraints form capture of PBH in stars fall right in the unconstrained mass range
- Constraints form ordinary stars might follow from already existing observations, provided the parameter ξ can be reliably determined

BACKUP

- The density of bound DM, assuming Maxwellian parent distribution with v_∞:

$$\rho_{\rm bound} \sim \rho_{DM} \left(\frac{\phi_0}{v_\infty^2} \right)^{3/2} = {\rm const} \cdot \frac{\rho_{DM}}{v_\infty^3}$$

- DM after the adiabatic contraction:



- Number of particles within r,

$$n(r) \propto r^{3/2}$$

- Number of particles with periastron $< r$, that is, on trajectories passing through star

$$\nu(r) \propto r$$

Constraints from capture at formation

Assuming $\rho_D = 10^4$ GeV/cm^3 and $v = 7$km/s